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APPLYING THE TECHNIQUE OF INFRARED PHOTOGRAPHY TO WALL TEMPERATURE MEASUREMENTS IN ROCKET MOTORS

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ABSTRACT

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A description of photographic techniques using radiation-sensitive emulsions for temperature measurements, based on the relative degree of film darkening as determined by a Huet photoelectric microdensimeter. The theory of the relationship between film density and temperature is developed, followed by practical considerations on the type of film, camera, lens opening, exposure, and developer. A description of the experimental procedure for setting up reference curves as a standard for the temperature measurement follows. A specific example of measurements made on a particular rocket engine is given, from which the inherent advantages of this technique are evident, in that not only are temperature measurements for any particular small area possible, but they are quantitative as well as qualitative.

Author

The most commonly used method of measuring the temperature of a /1* hot metal wall, like that of a rocket motor nozzle during operation, is to embed thermocouples at various points on the surface and to record their output signals. It is, however, also possible to measure this temperature from infrared photographs -- this is the method which we are about to describe, the advantages of which we shall define.

I. PRINCIPLE OF THE METHOD

1.1 General Statements

A sector of a hot metal wall emits radiation whose spectrum extends from the far infrared to the ultraviolet. In the temperature range from 700 to 1200° C, which covers the method applications up to the present, the bulk of the radiated energy is in the infrared spectrum.

Therefore, the darkening of a film whose emulsion is sensitive to this radiation will vary as a function of the temperature of the wall photographed.

By measuring this darkening of the film, we may determine the temperature if we have a connection between these two variables, for example, through the interpretation of a calibrated standard.

The relative darkening density (with respect to the fogged portion of the film: the unexposed portion) is measured by a Huet microdensitometer having a photoelectric cell. The analysis is semi-automatic; the temperature distribution curves are obtained on a Sefram Graphispot recording instrument.

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* Note: Numbers in the margin indicate pagination in the original foreign text.

We work with practically monochromatic light by placing a high-pass filter in front of the camera lens (the resulting maximum spectral sensitivity is then about 0.85 microns). This is done so as not to have to take into account the variations in the emissivity of the radiating body as a function of wavelength (which is close to 0.8 -- gray body), and also so that a single temperature, and consequently a single density, will correspond to an energy level of λ_ε.

1.2 Theory

(a) Relation Between Density and Temperature

The energy radiated by a surface sector brought to temperature T in a band of wavelengths λ_1, λ_2, where $\lambda_2 = \lambda_1+\Delta\lambda_1$, is

$$W = \int_{\lambda_1}^{\lambda_2} \varepsilon_\lambda(T)\, r_\lambda(T)\, d\lambda \qquad (1)$$

where ε_λ is emissivity and r_λ is the energy radiated by a black body, /2 while according to Wien's formula $r_\lambda = C_1\lambda^{-5}\varepsilon^{-C_2/\lambda}$ (C_1, C_2 are constants). If k_λ is used to designate the emissive output, then W', the energy received by the film, is

$$W' = k_\lambda W \qquad (2)$$

but optical density D of the image is given by

$$D = \gamma_\lambda \log a W' \qquad (3)$$

where a depends on the aperture and exposure of the camera; γ_λ is the gamma of the emulsion or the slope of its characteristic curve; and D = F (log of illumination) = F (log Ext) in the straight-line portion of this characteristic curve. From a practical point of view, $03 \leqslant D \leqslant 1.8$. For the filter used (Wratten, 87c), we have $\lambda_1 = 0.8\mu$, $\lambda_2 = 0.9\mu$. From

formulas (1) and (2) we derive

$$D = \gamma_\lambda \log\left(a k_\lambda \int_{\lambda_1}^{\lambda_2} \xi_\lambda(\pi)\, r_\lambda(\pi)\, d\lambda\right)$$

(b) Concept of Relative Density

The unexposed film has a certain amount of darkening (background fogging) with respect to absolute transparency. The exposed film may be compared with two thin superposed plates, one of density D_o (background fogging), the other density D_t (emulsion darkening). A third plate of density D_c (optical adjusting wedge) is superimposed on the other two. Let ϕ be the flux incident to the first plate and ϕ_c the resultant flux leaving the third plate and entering the photoelectric cell of the microdensitometer. We have

$D_o = \log \frac{\phi_o}{\phi}$, where ϕ_o is the flux leaving the first plate.

The resultant density is $D = D_o + D_t + D_c = \log \frac{\phi}{\phi_c}$.

From the electrical point of view

$$D = \log \frac{i_{max}}{i_o} \qquad i_{max} = K i_o e^D$$

as D passes from zero to ∞, i_{max} passes from Ki_o to 0. /3

The galvanometer utilized has an exponential scale from right to left with zero at $Ki_o = 0.5\mu A$. By means of the optical wedge $Ki_o = 0.5\mu A$ is adjusted on an unexposed area of film.

1.3 Practical Considerations

(a) Film

The emulsion used is infrared Kodak film with a sensitivity

gap in the green (0.5 to 0.6μ) and a maximum spectral sensitivity at about 0.85μ.

(b) Developing the Film.

Bath DK 76: 7 minutes at 20°C; washing; fixing in a standard bath for 30 minutes; washing 45 minutes; drying in heat.

(c) Camera

Praktina with lenses of 150 or 300 mm focal length, depending on distance; aperture -- 4 to 32; exposure time -- 1 second to 0.001 second.

(d) Microdensitometer

Huet make; width of available slits -- 0.12, 0.22, 0.32, 0.42, 0.52, 0.72 mm; height of available slits -- 2.4, 4.8, 7.2, 9.6 mm.

(e) Example of Use

Distance from object depicted [to lens] -- 8 m; lens focal length -- 150 mm; microdensitometer slit -- 0.52 x 4.8 mm^2; projection of plate magnification -- 10 X.

An opening of 0.52 x 4.8 mm corresponds to approximately one square centimeter of nozzle surface.

II. CALIBRATION. CORRELATION BETWEEN DENSITIES AND TEMPERATURES

As previously pointed out, we must be able to correlate density and temperature. For this purpose, we plotted a network of curves giving the relative darkening density as a function of temperature with camera aperture and exposure time as parameters. To do this, we used emitter tubes made of metal similar to that used for the ejectors. Temperatures

up to 1250°C were controlled by thermocouples, so that we might have an emissivity close to calibration during the tests. Temperatures above 1250°C were controlled by an optical pyrometer as seen in slide 1.

On the basis of this network of curves, we can state that the measurement possibilities are as follows (limitations due to camera characteristics): range -- 550 to 1250°C by increments of 150°C.

In order to extend the range toward higher temperatures, we used a Tri-X emulsion and a Wratten 29 filter. The resultant maximum sensitivity was then about 0.65μ. It was thus possible to reach about 1500°C, always by increments of 150°C (to illustrate, for $1300 < T < 1450$°C, we opened up to 22 with a 0.001 second exposure).

III. DEVIATIONS IN THERMOCOUPLE MEASUREMENT. CAUSES OF ERROR /4

During the tests we performed measurements simultaneously by thermocouples and by photography. The thermocouples were placed in the photographed area (as you will see from the slides to be shown in a few moments), and this made it possible to compare the two methods. In general, the spread in results does not exceed $\pm 5\%$ despite the numerous causes of possible error, such as:

(1) variation in emissivity between test and standard (if ε varies from 1 to 0.6, the variation in emitted energy introduces only a 6% error on the temperature for $\lambda = 0.85\mu$),

(2) interposition of absorbent fumes between ejector and camera,

(3) variation in spectral sensitivity between films,

(4) differing developing conditions,

(5) inherent thermocouple errors (attachment capsule etc.), and

(6) microdensitometer error.

IV. EXAMPLES OF METHOD APPLICATION

The technique just described can render great service in adjusting hot-wall nozzles, such as are found in solid-fuel propulsive units or non-refrigerated liquid-fuel engines with ergol circulated in a double wall. The value of the method lies not only in furnishing an instantaneous chart of temperature distribution on the nozzle wall, but also in permitting the scaling of this chart, and consequently in evaluating the anomalies which it discloses -- overheated points or areas, temperature inequalities between two adjacent areas involving thermal stresses, etc.

The slides which we are going to show were taken at the Laboratory of Ballistic and Aerodynamic Research while testing liquid propergol engines tested by that institution. The first slide represents the skirt of a nozzle after about twenty seconds of operation. This skirt, made of sheet metal several millimeters thick, is cooled by a film of fuel applied to the inner face of the wall by a number of holes which feed a distributing collar situated after a great circle of the skirt and partly visible in the photo. A small fraction of the fuel, cut off at the level of the combustion chamber injector, reaches the distribution collar through the vertical channels, likewise visible in the shot. The metal wall above the distributor, at the level of the nozzle neck, is protected by a graphite block and therefore remains cool enough not to make an impression on the film.

The image clearly shows that the film is injected by individual holes. It enables us to trace the boundary between the cool sector, where the film is still liquid, and the hot sector where the film has

the form of a boundary layer which is cooler than the central core, but nevertheless elevated to a temperature of several hundred degrees. The vaporization boundary flows vertically down the distributor feed channels -- which proves that the film is more plentiful in this sector, where the temperature is about a hundred degrees lower than that in the bright region visible at the left of the picture.

The next shot was taken several seconds later during the same test. /5 It shows that the vaporization limit of the film is still displaced perpendicular to the fuel intake in the distributor, but also that the temperature irregularities tend to be resorbed. The temperature differential between the right and left sector is no more than about $50^{\circ}C$.

The following examples deal with nozzles whose skirts are not directly protected by a film of fuel injected downstream from the neck. Protection is provided simply by the relatively cool boundary layer coming from the film which cools the walls of the combustion chamber. This film is applied to the wall by a series of holes in the base of the injector, as we see in slide 3. Fuel is fed to the injector by the two diametrically opposed elbow pipes, also visible in the shot. These pipes empty into an annular space, and the fuel which they discharge is distributed around the periphery of the injector, so as also to feed the spray holes by means of a balancing ring lined with a fine screen.

It happens that the balancing ring and screen do not distribute the fuel equally around the circumference of the chamber. The linear

discharge of the coolant film is not the same in different sectors of the nozzle, and this effect is also evident down into the divergent part, as photo 4 indicates. This view was taken after about two minutes of operation. The entire skirt wall is at an average temperature which ranges from 950°C (gray portion downstream from the neck) to 900°C or less (black portion near the exhaust section). But a very narrow section comprised between two power sources, which are very easily located photographically, is brought to a temperature close to 1000°C. This example is a perfect illustration of the procedure's remarkable sensitivity, which, of course, is associated with a measurement scale of no more than 150°C. On the other hand, it clearly illustrates how difficult such a narrow overheated zone would be to detect in an indisputable and systematic fashion with thermocouples distributed over the wall, even if their disposition were extraordinarily dense.

The gas jet at the engine's exhaust has not been screened in this photo, in order to make it clear that in the slightly-overheated sector the protective boundary layer has less fuel than the adjacent sectors, but is distinctly hotter. This is the reason that this sector stands out clearly against the background of the flame, all the more so because the fuel vapors, which are much hotter in this zone, burst into flame more quickly on contact with the air than in the neighboring zones.

The following shot represents the same engine during another test, also after about two minutes of operation. With the same aperture, exposure time, and sensitivity for the two photos, we realize that the

skirt has heated more during the second test than during the first test. This is simply due to the fact that the pressure at the focus - that is, in the combustion chamber - was higher at the time of the second test than in the first: about 20 bars instead of 17. Therefore, heat transfer to the wall both by convection and radiation has increased. We would also like to note that the discharge of fuel supplying the coolant film has also increased. In fact, the total discharge of propergol into the chamber is proportional to the combustion pressure,and - due to the very design of the injector - coolant discharge is a constant and definite fraction of the total discharge. This condition, which tends to compensate for the rise in the heat transfer factors, does not, however, completely succeed, and equilibrium is shifted towards a higher wall temperature.

The over-all skirt is therefore hotter than in the preceding shot -- the temperature in the gray zone is on the order of 1000°C. As for the very bright zone, whose position is remarkably congruent with the slightly overheated zone already detected in the preceding slide, /6 it is raised to a temperature close to 1100°C. The differential between the hot and cool sector here reaches 100°C, as against only 50°C when operating at lower pressure. The reason for this is that the balancing ring, which is no longer perfectly distributing the nominal amount of the fuel around the injector periphery, loses some of its efficiency when an amount is accumulated.

Photo 6 illustrates the possibilities of special Tri-X films. This is a shot of the skirt of an ejector designed for the second stage of the European satellite launcher after about 100 seconds of operation.

The characteristics of this motor have been pushed to the limit, and the entire skirt shown is raised to a temperature very close to 1100°C from the 60th second of operation. At this temperature, an ordinary infrared film - considering the apertures and exposure times which are practicable with present cameras - would be practically saturated and the photo could not therefore show the zones of likely overheating. Tri-X film, on the contrary, is far from saturation since its measuring range goes to about 1450°C, and the uniform hue of the slide projected simply indicates the proper distribution of the coolant film on the inside of this nozzle.

V. CONCLUSION

These shots taken in the infrared afford research and test engineers significant help in adjusting hot-wall nozzles. They offer remarkable opportunities for fine and detailed analysis of thermal effects undergone by the tested material, not only qualitatively, but also -- and this is the essential advantage of this method -- quantitatively. In fact, if the presentation of various defects in a cooling system is the first step toward remedying them, a quantitative estimate of the gravity of the defect detected is indispensable in clarifying the decision to be made by the one who must remedy and evaluate it.

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